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Communication Channel Modeling and Automata Designing of Human Auditory System

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***Abstract*—This paper discussed about the molecular communication within the ear of human body. That most important task of human ear is to take to make human sensitive to each frequency of sound as well as balancing. The purpose of this paper is to first design a novel channel model of human inner ear related to the working of underlying molecular communication network. Hearing ability of human ear is taken as the basis of this work. Later a Moore machine is designed based upon the derived communication channel activities of human auditory system. The proposed work would certainly help to design a similar nano computer that will pave the path to diagnose of serious malfunctionalities in human body which incur communication failure including human ear through advanced ICT paradigm.**

***Index Terms*—Human ear, cochlea, electrochemical impulse, auditory nerve, moore machine, nano communication network, finite state automata.**

I. Introduction

Present age is bearing the fantastic behavior of advanced technologies. Nano technology is one of those. Nano technology is a promising area of technology which has led many important innovations and established scientific truths. Nano communication is the method of interaction between nano particles, which may include human built artificial components such as nano computer or quantum computer or natural entities such as, red blood cells, neurons etc. The network which is built by combining these nano objects to communicate in better systematic way is known as nano network. Human body is a nature built complex workshop which has unlimited number of nano networks in it, such as nervous system, endocrine system, hormonal communication system etc. Auditory system is one of those.

Auditory system is one of the five sensory systems which are responsible for hearing sound. Auditory system is made of ear and auditory nerves. Ear is subdivided in three parts such as, outer, middle and inner ear. Outer ear is mainly sum up of pinna which acts as reflector and attenuator of incoming sound and auditory canal which is a simple tube that amplifies sound waves of 4-12 KHz range by preceding the sound to eardrum. Middle ear processes the sound wave that hits ear drum (tympanic membrane). The information obtained herewith is passed through three delicate bones named: malleus, incus and stapes and converts the low pressure eardrum sound into high-end sound wave. Inner ear converts the sound wave into nerve impulses. Cochlea is the main part of it. Cochlea contains three fluid based sections such as, basilar membrane which separates two sections. One is scala media containing endolymph and the organ of Corti which converts mechanical sound waves to electrical signals, is another part of inner ear. The other section has scala tymphani and scala vestibuli situated within labyrinth which is filled with perilymph [1]. The potassium (K^+) and calcium (Ca^{++}) ions in the endolymph and perilymph develops the electrical potential difference. Hair cell is the other constituent of inner ear. This cell is of two types such as, inner and outer hair cell. Inner hair cell directs the sound wave into electrical counterpart whereas outer hair cell acts as motor. Ninety-five percent of the VIIIth nerve afferents synapse on inner hair cells [2]. Tectorial membrane movement atop hair cells. By the up-down movement of basilar and tectorial membranes compels the cilia to laterally bend by pulling opening the trap door channels which causes influx of potassium followed by calcium to transmit the neurotransmitter which later causes an EPSP to initiate action potentials synapses of VIIIth cranial nerve [2].

Moore machine is a finite state automaton where output is solely dependent on its current state. It is a theoretical basis of any computation in automaton model.

This paper assumes the hearing mechanism as auditory system in human body to develop a similar computational model based on automaton. The whole process relies on the working of communication channel of the auditory system. For simpler and better understanding of hearing mechanism in human body, the presented communication channel model takes the basic events and structural aspects of auditory system.

This paper is novel in its way of assumption and representation of auditory system. This work surely establishes a foundation for own kind of communication channel which surely paves the path of advanced ICT based diagnosis of human diseases caused by communication error whether it is genetic or incurred. The goal of this paper is to setup a theoretical basis to enable the futuristic diagnosis techniques to be built upon communication network by adding primary research practice towards the nano communication network design of human body, where a limited work has been done till date.

This paper is organized as follows. Section II presents related work. Section III presents basics of automata theory and Moore machine. Section IV presents the communication channel design of auditory system. Section V represents automata modeling of auditory system.

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II. Related work

Literature [5] proposed a Moore machine model, adapted by comprehending biological interactions between nano scale neuro-spike communication and devises nano computer model based on Moore machine. [6] has recently proposed a novel automata modeling of hormonal molecular communication channel in human body which is followed by a nano machine design. [3] discussed how the nervous system processes auditory information by combining knowledge from anatomy (to know which structures participate), electrophysiology (that tells us the properties of these structures), and finally, mathematical modeling (as a powerful tool for studying the mechanisms of the observed phenomena). [4] presented various elementary models for significant intra-body molecular communication channels, including nanoscale neuro-spike communication channel, action potential-based cardiomyocyte molecular communication channel, and hormonal molecular communication channel along with multi-terminal nanonetworks extensions of channel models, with emphasis on the nervous, cardiovascular molecular, and endocrine nanonetworks. Thesis [7] represented the modeling of Finite State Automata (FSA) of Quorum Sensing mechanism in Bacteria and designs a nanomachine to implement Quorum Sensing. Paper [8] proposed synaptic Gaussian interference channel along with the characterization of power or firing rate of achievable rate region for the channel. [9] proposed an information theoretical model to understand the signaling mechanism of the molecular communication medium. In [10], an analytical framework that incorporated the effect of mobility into the performance of electrochemical communication among nanomachines is presented. Literature [11] proposed a stochastic dynamical model of noisy neural networks with complex architectures and discusses activation of neural networks by a stimulus, pacemakers and spontaneous activity.

III. Automata theory and Moore machine

Automata theory discusses the mathematical machines and the mechanism of solving mathematical problems with it. Automata theory deals with automaton as the basis which is supposed to run with given input strings known as alphabets from a set of symbols or letters. Upon reading the inputs in each discrete time steps the automaton accepts particular word. An automaton consists of finite set of states. In one instant of running time, the automaton is one of its states. When a symbol is read the automaton transits itself from the current state to next state based on the function which contains current state and input as parameters, named as transition function. Automaton is said to have reached at final state when the whole input is processed. Final state is the accepting state which accepts a given word. Language is the set of all words which are accepted by the automaton. The definition of finite state automata is presented below:

A deterministic finite state automaton is a system $A = \{Q, \sum, \delta, q_0, F\}$, *where Q is a finite set of the possible internal states of the automaton A,* $\sum$ *is a finite alphabet,* q_0 *is the initial state,* δ *is the transition function* ($\delta: Q \times \sum \rightarrow Q$) *and F is a subset of Q, the set of final or acceptance states.*

Moore machine the finite state automaton which takes present state as the sole input and proceeds to next state based upon the relevant transition of the transition function. It is a six-tuple set presented below.

A Moore machine is a six-tuple $A = \{Q, \sum, \Lambda, \delta, \tau, q_0\}$, *where Q is a finite set of the possible internal states of the automaton A,* $\sum$ *and* Λ *are finite alphabets for the input and the output, respectively,* q_0 *is the initial state,* δ *is the transition function* ($\delta: Q \times \sum \rightarrow Q$) *and* τ *is the output function* ($\tau: Q \rightarrow \Lambda$).

IV. Communication channel design of human auditory system

This section describes the communication channel design based on biological functions of human auditory system. Fig 1. represents the overall structure of human auditory system.

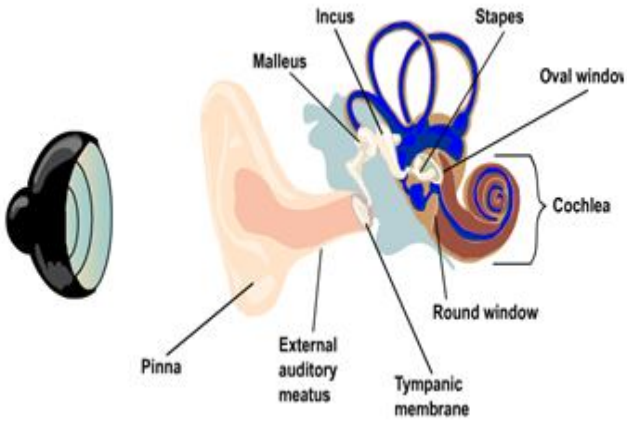

Fig 1. Sound wave propagation towards inner ear.

System starts functioning by taking sound wave as input through the pinna of outer ear. The sound wave then propagates towards inner ear by generating vibration in tympanic membrane followed by malleus, incus, and stapes to convert the low pressure eardrum sound into high-end sound wave. The inner ear is the innermost part of the human ear shown in Fig 1. It consists of two functional units. One the hollow coiled structured cochlea and another one is the vestibular apparatus. The structural and functional unit of cochlea is the organ of corti which includes sensory hair cells, the key structure of hearing system. This system also consists of basilar membrane, Reissner's membrane, and three scalae or chamber bathed in perilymph fluid. The vestibular system containing the converged semicircular canals, close to the cochlea filled in endolymph. The chemical differences between Ca++ and K+ generates potential difference which then transmits the electrical signal of the acquired sound wave to the VIIIth cranial nerve for further processing of brain.

Fig 2. represents the inner ear auditory pathways and

Fig 1. is used with permission from Lincoln Gray, Ph.D., Department of Communication Sciences and Disorders, James Madison University, http://neuroscience.uth.tmc.edu/s2/chapter12.html

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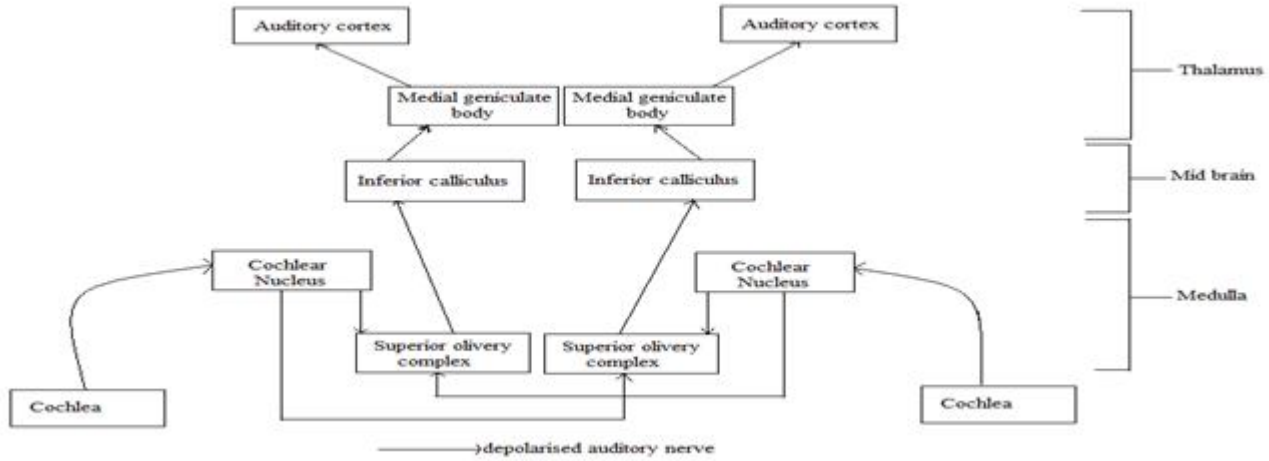

Figure 2. Inner ear part of auditory system of human body.

reflexes. As per the above figure auditory signal starts its inner ear journey from cochlea. Then it moves towards inferior calliculus through cochlear nucleus and superior olivery complex. Later on the continuation of signal retains to auditory cortex via medial geniculate body. The journey from cochlea to superior olivery complex is monitored by medulla of brain whereas signal processing of inferior calliculus and from medial geniculate body to auditory cortex is flagged by mid brain and thalamus.

play vital role as controller of the system combined with the noise input (N_i) into the system. Noise input can be anything among temperature, intensity of sound, ear drum sensitivity etc. Endolymph and perilymph are two fluids which surround the hair cells, rich in potassium and fills labyrinth, respectively. Potassium (K^+) and calcium (Ca^{++}) ions in the endolymph and perilymph originates ion influx which in turn produces the potential difference.

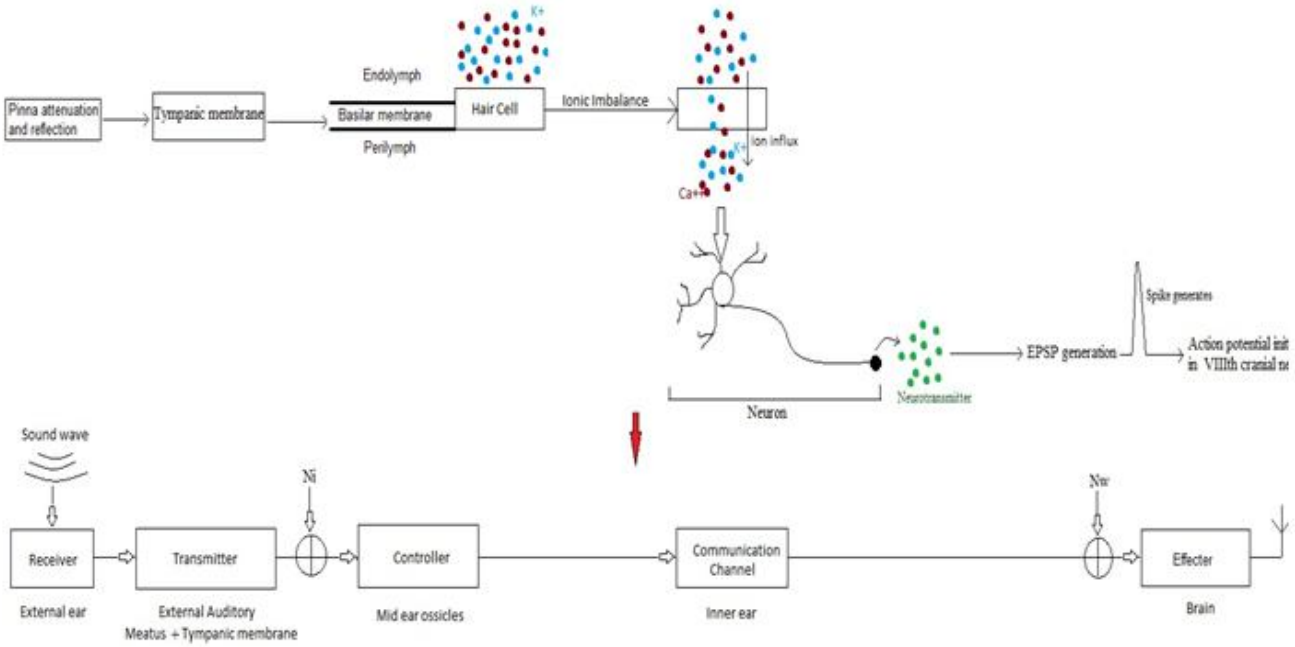

Figure 3. Communication channel model of auditory system of human body.

Fig 3. describes the realistic communication channel model of the human auditory system. The figure is divided in two portions. Above portion presents molecular level communication mechanism of auditory system. Lower portion shows the realistic communication channel model. Pinna reflects and attenuates the sound wave and passes to inner ear via middle ear. This can be modeled as receiver of any communication system in electro-mechanical world. Tympanic membrane and outer auditory meatus altogether take the form of transmitter of the sound wave of the proposed model. Mid ear ossicles

The generated electric signal is then directed to dendrites of nerves resulting neurotransmitter ejection and EPSP generation. EPSP in turn produces spike which is transmitted towards VIIIth cranial nerve. The activities of inner ear do the job of communication channel of the system. N_w-noise is added to the signal in synaptic disturbance form leading brain to act as effecter.

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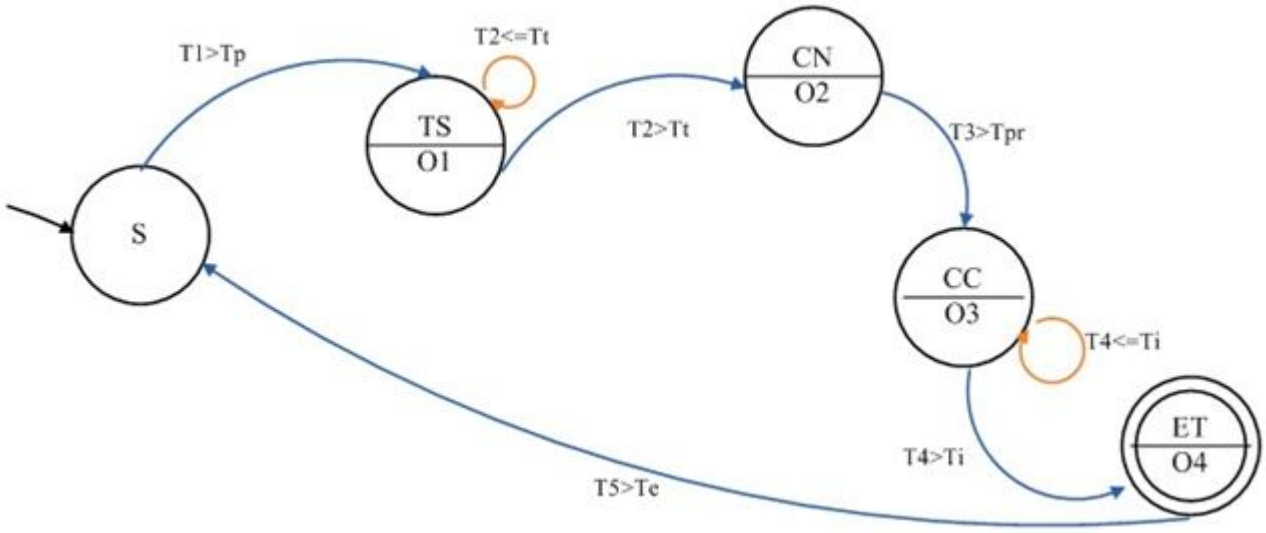

Figure 4. Communication channel model of auditory system of human body.

V. Automata Model Of Auditory System

Table I. Input Values And Assumptions

Input values	Assumptions	Input values	Assumptions
T_1	Pinna attenuation factor	T_p	Pinna attenuation threshold
T_2	Tympanic vibration factor	T_t	Tympanic vibration threshold
T_3	Pressure factor	T_{pr}	Pressure threshold
T_4	Ion influx factor	T_i	Ion influx threshold
T_5	EPSP factor	T_e	EPSP threshold

- *Moore machine states:* The Moore machine presented in Fig. 3 has six states: Q={S, TS, CN, CC, ET}

Table II. Alphabet-$\sum$

Input	Resultants
d_1	$T_1>T_p$
d_2	$T_2<=T_t$
d_3	$T_2>T_t$
d_4	$T_3>T_{pr}$
d_5	$T_4<=T_i$
d_6	$T_4>T_i$
d_7	$T_5>T_e$

- *Moore machine alphabets:* The Moore machine has seven alphabets shown in Table II. $\sum$= {d_1, d_2, d_3, d_4, d_5, d_6, d_7}
- *Moore machine output alphabets:* The Moore machine has three output alphabets: Λ= {O_1, O_2, O_3, O_4}
- *Moore machine output function:* The Moore machine output function is presented in Table III.
- *Moore machine start state:* The Moore machine start state is: q_0=S.
- *Final state:* The Moore machine final state is: F=ET.

d_x/ϵ - presents the action/event concept where x-1,2,3,…,7. ϵ is the event that means impossible or illegal event shown in Table IV.

Table III. Output- τ

States	S	TS	CN	CC	ET
Output	ϵ	O_1	O_2	O_3	O_4

Table IV. State transition table

	S	TS	CN	CC	ET
S	---	d_1/O_1	---	---	---
TS	---	d_2/O_1	d_3/O_2	---	---
CN	---	---	---	d_4/O_3	---
CC	---	---	---	d_5/O_3	d_6/O_4
ET	d_7/ϵ	---	---	---	---

The Moore machine devised in this section comprises five states; S, TS, CN, CC, and ET (Fig. 4). Moore machine starts from state S-receiver of the system which receives sound wave from external world. Automaton when reads d_1 as input, transits from S to state-TS and producing output O_1. TS represents transmitter part of the auditory system which when reads input d_2 produces output O_2 but retains at same place. Given input d_3, TS goes to CN state and accordingly produces output O_3. CN presents controller of the system which takes input d_4 and moves to CC state and

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produces O_3. CC retains itself when takes input d_5 and produces output O_3. CC moves to final state ET of the automaton taking d_6 as input O_4 to output. Lastly, ET again goes to S when input d_7 is read and produces õ as output.

Table III presents output functions of the automaton. O_1 presents the production of vibration with the force of the sound wave that strikes tympanic membrane and transmits the vibrations further into bones of the inner ear. O_2 represents the conversion of low pressure sound to the high end pressure i.e. amplification of sound wave. O_3 is the generation of electrical counter part of input sound signal in inner ear by EPSP production. O_4 is the final signal transition through VIIIth cranial nerve towards brain.

The automaton presented in this paper takes few assumptions on few alphabets. Table I presents the inputs of the automaton and assumes few parametric theories. Input and the resultant values such as in Table II is the basis of the automaton; $d_1$represents $T_1>T_p$, d_2 is same as $T_2<=T_t$, d_3 is equal to $T_2>T_t$, d_4 is $T_3>T_{pr}$, d_5 represents $T_4<=T_i$, d_6 means $T_4>T_i$, and d_7 equals to $T_5>T_e$. Here seven inequalities have been proposed each defining a single input to the automaton.

Table III presents the output function. States S, TS, CN, CC, and ET are associated with outputs as: õ, O1, O2, O3, and O4 respectively.

This automata model of auditory system is a novel approach of its own way.

Conclusions

This paper devises the novel communication channel model of human auditory system. The communication channel is based on the realistic biological interaction between various macro organs and nano organs. Receiver, transmitter, controller, communication channel and effecter as a whole describe the communication channel of auditory systems. External ear, middle ear and inner ear altogether combine to make a auditory system which links up with nervous system as well in human body.

The automata model of the auditory system establishes a foundation of own kind of nanonetwork designing basis which surely paves the future path towards the ultra advanced ICT based medical diagnostic system.

This work is novel and puts the base of nanonetwork development from human auditory system. This approach is purely theoretical but is very much able to get transformed into a real implementation. Nanonetwork designing of human body is itself a new research topic which is going to make a new horizon of advanced medical diagnostic approach. This nanonetwork development work surely lacks from a few parameters. This design lacks its protocol implementation in real life. Very simple approach towards designing this automaton cuts-off many complex behavior and functionalities of auditory system. Though this research is in very beginning stage but it lay down the future movement of similar kind of research into new paradigm. Proper simulation environment should be developed to check the reliability and efficiency of the auditory system. Nervous communication is to take as much fined way so that the development process could be further be taken ahead.

Acknowledgment

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